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Measurement of Turbulence in Pressurized Pipe Flow Using Particle Image Velocimetry

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MEASUREMENT OF TURBULENCE IN PRESSURIZED PIPE FLOW USING PARTICLE IMAGE VELOCIMETRY

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Abstract: Invasive mussel species can cause problems at a variety of water resource facilities by colonizing within piping systems, significantly reducing flow capacity. Exposing mussels to intense turbulence as they enter the system may be effective in reducing mussel settlement downstream. To quantify turbulence in a pressurized pipe, Particle Image Velocimetry (PIV) measurements were made downstream of a newly developed pipe fitting designed to generate intense turbulence for mussel control. Two-dimensional (2D) velocity data were collected throughout the pipe profile at various distances downstream of the fitting and were analyzed to quantify hydrodynamic properties of the turbulent flow including dissipation rate and Kolmogorov length scale. Results indicate that the fitting generated sufficient turbulent energy to drive the microscale length down to scales expected to influence invasive mussel species (near 200 μm). Spectral analysis of spatial data also revealed that near the Kolmogorov scale, energy was increased by more than one order of magnitude for a mean pipe velocity of 0.914 m/s and just less than one order of magnitude for 1.83 m/s.

Keywords: PIV, turbulence, energy spectrum, pipe flow.

INTRODUCTION

The main objective of this research was to quantify turbulence characteristics produced by a turbulence generation system designed to prevent invasive mussel colonization in pipes. Many water resource facilities such as dams, power plants, pumping plants, and irrigation systems have complex piping systems that are susceptible to mussel colonization (RECLAMATION 2009). Past research has indicated that turbulence in the flow field may reduce the impacts of mussel settlement on water conveyance and distribution systems (REHMANN et al. 2003). Their study showed that juvenile mussels (veligers) are more likely to be killed or injured when turbulent eddies are near the same size or smaller than the veliger, exposing them to damaging velocity fluctuations and shear stresses. Another study reported that veligers were “fragile” and “highly susceptible to damage by physical forces…” (AMEC EARTH & ENVIRONMENTAL 2009). Similar results were found with other organisms such as plankton (PETERS and MARRASE 2000).

While most research of turbulence effects specific to quagga and zebra mussels has been performed in open channel situations, piping systems may also benefit by using turbulence as an effective mussel control. This study attempts to prevent mussel settlement in pipes by exposing them to intense turbulence as they flow through a specialized pipe fitting (turbulence generator). The turbulence generator is an active system that adds energy to the pipe flow without causing additional head losses. Details are not provided due to intellectual property concerns of the client. PIV was used to quantify hydrodynamic properties throughout the entire flow field downstream of the turbulence pipe fitting. PIV uses successive image pairs of illuminated particles in the flow field to create a 2D map of the velocity vectors and has been widely used to study turbulent flows (SAARENRINNE et al. 2001 and FOUCAUT et al. 2004) including turbulence effects on living organisms (PETERS and REDONDO 1997).

Turbulence parameters in a circular pipe were measured and quantified in Reclamation’s Hydraulics Laboratory in Denver, CO. Turbulence parameters were measured within the downstream pipe profile to determine how they evolved with distance for two key pipe velocities (max. and min. of typical velocity range). Also, turbulence levels of common pipe flow were compared to turbulence generated by the specialized pipe fitting to quantify any gains in intensity. Results are valuable for future research efforts on pressurized pipe turbulence and its effects on invasive mussel species as well as using PIV methods for turbulence measurements in circular conduits.

TEST PROCEDURE AND MEASUREMENT

Measurements were made in a 0.203 m ID clear acrylic pipe test section directly downstream from the turbulence generator. The test section was level and was surrounded by a rectangular water jacket. A long straight section of pipe (≈ 18 pipe diameters) allowed a uniform flow profile to develop upstream before arriving at the turbulence generator. Measurements were made at two mean flow velocities (*U*) shown in Table 1 with and without additional turbulence generation.

PIV images were taken of the pipe profile at 7.4 Hz and locations 1, 2, 5, and 10 pipe diameters downstream from the generator. Image size was 182.3 x 182.3 mm (2048 x 2048 pixels) of which only the top 105 mm portion of the image was analyzed (assumed symmetrical flow characteristics). Based on a sensitivity analysis (Fig. 1), 200 image pairs were required for testing as turbulence intensity and standard deviation stabilized.

Images were analyzed with the Flow Manager PIV software using cross correlation of 16-pixel x 16-pixel interrogation windows with a 50% horizontal and vertical overlap. Gaussian windowing and a No DC filter were used. A moving-average validation was applied to remove and substitute any vector that varied more than 10 percent from its neighbouring vectors (Table 1). Flow was seeded with clay particles with an average diameter of approximately 80 μm.

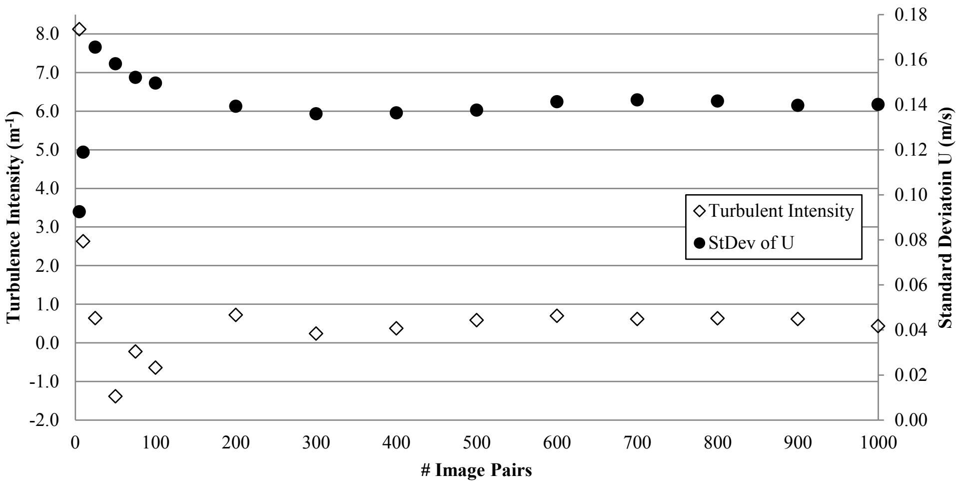

Figure 5 – Sensitivity analysis of number of image pairs.

The verified 2D vector data were imported into TecPlot where they were manipulated to find key turbulence parameters. As the eddy sizes neared the same scale as mussel veligers of particular interest to this study, the Kolmogorov length scale (TENNEKES and LUMLEY 1972) was the key parameter and was estimated using equations 1 and 2:

$$L_k = \left(\frac{\nu^3}{\epsilon_D}\right)^{\frac{1}{4}} \tag{1}$$

ν is the kinematic viscosity and ϵ_D is the energy dissipation rate, which was estimated directly from the 2D velocity vector data by equation 2 (GRUE et al. 2004).

$$\epsilon_D = 3\nu\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial v}{\partial x}\right)^2 + 2\left(\frac{\partial u}{\partial y}\frac{\partial v}{\partial x}\right) + \frac{2}{3}\left(\frac{\partial u}{\partial x}\frac{\partial v}{\partial y}\right)\right] \tag{2}$$

Table 2 – Pipe flow characteristics and PIV vector validation.

U *m/s*	Re *no turbulence generator*	Avg % Substituted Vectors	Max % Substituted Vectors
0.914	189,000	2.77%	3.67%
1.83	378,000	8.29%	12.25%

Also, spectral analysis was used to compare the energy cascade of the various pipe flows. Spatial velocity data (stream wise velocity vector, u_1), taken through a vertical cross-section 1 diameter downstream of the generator, were used for the spectral analysis. This location was chosen because it was the location nearest the turbulence generator that could still be seen with the PIV, giving the closest representation of flow affected by the generator. Methods shown by DORON et al. (2000) were used to develop the energy spectrum from spatial data.

RESULTS

Turbulence measurements were made directly downstream of the generator section to show any additional turbulence a mussel may experience after passing through the generator. While it was not possible to make measurements within the generator section itself, the hydrodynamics in this downstream test section indicate the necessary level of generator operation for mussel control. Due to the high level of mixing at the measurement locations no flow structures were visible from the PIV images.

Images were captured at various locations from the generator to determine how far downstream the turbulence was sustainable. Figure 2, which is a plot of the average L_k values within a profile image, shows that any additional turbulence created by the fitting dissipates before reaching 5 pipe diameters downstream where measurements nearly match those of regular pipe flow. However, significant drops of L_k at 1 and 2 diameters downstream (Table 2) indicate that the generator significantly affects the turbulence levels for a small distance downstream before it is dissipated. Future demonstration testing at a field site with live quagga mussels will show whether or not mussel veligers are actually affected by the turbulence.

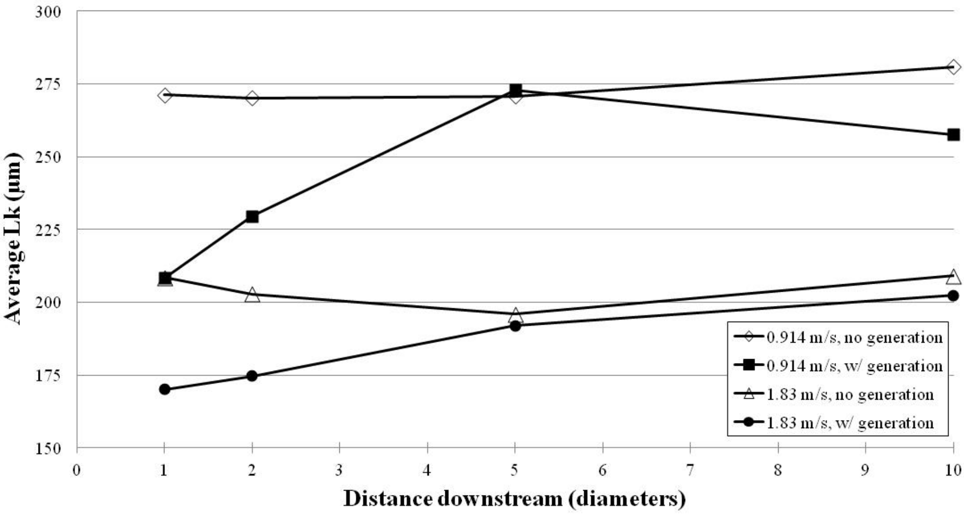

Figure 6 – Average L_k values throughout the pipe profile image at various distances downstream of the turbulence generator.

Spectral analysis is helpful in identifying which turbulent scales contain the most energy. A spectral comparison of velocity data show if there is a significant increase in turbulence energy caused by the generator, particularly at higher wave numbers near the Kolmogorov scale. Figures 3 and 4 show the energy spectrum of spatial velocity data taken vertically through the pipe section at 1 diameter downstream of the generator. $E(k_1)$ represents the mean energy at a particular wavenumber (k_1) which corresponds to eddy size scale. The energy cascade slopes shown in Figures 3 and 4 as well as Table 2 represent data near the higher end of the spectrum as the increase in energy near the Kolmogorov scale was of particular interest.

For U=0.914 m/s, the amount of energy was significantly increased by the generator for the entire spectrum (Fig. 3). The slope was flattened due to generated turbulence particularly near the higher end of the wave number spectrum indicating that significantly more energy was added to the smaller turbulent scales (more than 1 order of magnitude as shown in Table 2). This increase in energy near the Kolmogorov scale will hopefully have an impact on mussel veligers.

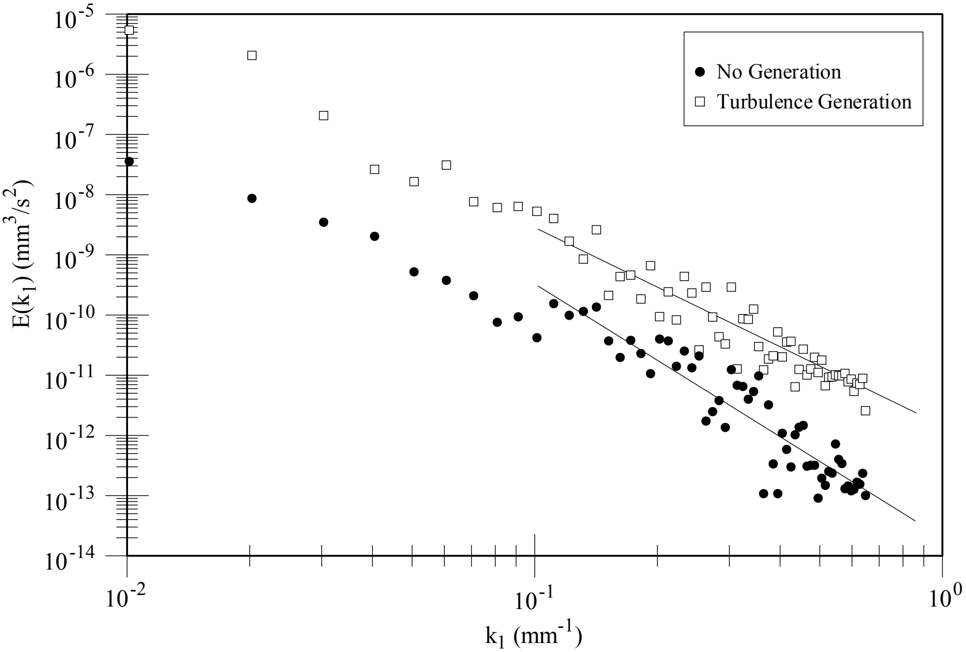

Figure 7 – Spatial energy spectrum of u_1 for U=0.914 m/s, 1 diameter downstream of generator.

Trends for U=1.83 m/s (Fig. 4) were similar but the effect was less significant than that for the lower pipe velocity. This is likely due to the greater natural turbulence of a higher Reynolds number flow. For this pipe velocity additional turbulent energy from the generator was a smaller percentage of the total flow energy as the level of generator operation was the same for both pipe flows. Still, there was a significant increase in energy at the highest wave number and the slope was flattened slightly (Table 2).

Scatter in the spectral data is likely due to differences in spatial velocities along the cross-section of the pipe. This location was chosen because it was the nearest possible cross-section to the generator that could be captured with the PIV and most closely represented turbulence levels within the generator. Also, spatial data were used rather than time series data due to the low frequency of the PIV system. Dense and thoroughly mixed seeding throughout the flow field made it possible to obtain accurate estimates of velocity and L_k values using PIV (PETERS and REDONDO 1997).

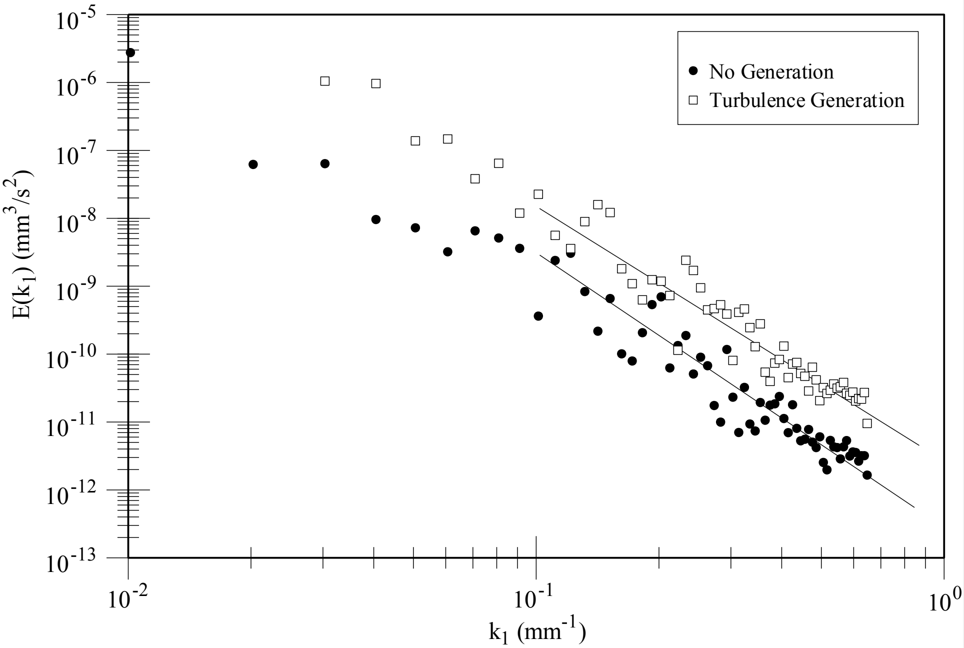

Figure 8 – Spatial energy spectrum of u_1 for U=1.83 m/s, 1 diameter downstream of generator.

Table 3 – Summary of results from figures 2 – 4.

U	**% Decrease in Avg L_k**		**Cascade Slope**		**Energy increase at L_k (max k_1)**
m/s	*at 1 dia. downstream*	*at 2 dia. downstream*	*Turbulence Generation*	*No Generation*	*orders of magnitude*
0.914	23.2%	15.1%	-4.82	-6.39	1.41
1.83	18.4%	13.9%	-2.32	-4.47	0.76

CONCLUSIONS

To determine if turbulence can be used as an invasive mussel control in piping systems, PIV measurements were made to quantify turbulence parameters in pressurized pipe flow. Data with and without generated turbulence were compared and showed that generated turbulence in the downstream pipe was sustained for about 2 diameters downstream. Within this range energy added from the generator drove the Kolmogorov length down to scales likely to impact invasive mussel species (near 200 μm). At 1 pipe diameter downstream, the energy spectrum showed that energy near the Kolmogorov scale was significantly increased for both pipe flows. The results of added energy and decreased eddy size, particularly at the Kolmogorov scale, will hopefully have a meaningful impact on invasive mussel species within piping systems.

NOTATION

U	=	mean pipe velocity (m/s)
u_I	=	stream wise velocity vector (m/s)
L_k	=	Kolmogorov length scale (μm)
v	=	kinematic viscosity (m^2/s)
ϵ_D	=	energy dissipation rate (m^2/s^3)
Re	=	Reynolds number of pipe flow (-)
k_I	=	wavenumber, corresponds to eddy size (mm^{-1})
$E(k_I)$	=	spatial energy spectra, corresponds to mean energy at wavenumber (mm^3/s^2)

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